LCGT Project Observing Gravitational Wave Events at 240 Mpc

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Abstract

The large-scale cryogenic gravitational wave telescope (LCGT) project was originally planned in 1998 and was revised in 2002. The design concept of the LCGT was to raise the baseline of TAMA by one order and to decrease the thermal noise of the mirrors by one order by using cryogenics and by locating LCGT at an underground site in Kamioka mine. Two sets of interferometers will be constructed in the same tunnel in order to reject possible fake events.

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In August, 2002, TAMA [2], LIGO (with three interferometers) [1,10] and GEO [4] conducted a collaborative observation with a time scale of one week. This data-taking-run was an epoch-making event in gravitational wave detection, because such observations will allow us to observe the signal of the coalescence of any neutron star binary occuring in our Galaxy. However, the ultimate sensitivity attained by these interferometers is not sufficient for frequent detection of the coalescence, because of the low occurrence rate, which is estimated at one event per million years for such a matured galaxy as our own. In order to observe more events, we need to increase the sensitivity of the detector so as to expand its scope range to cover more galaxies in the remote universe. The LCGT was originally planned in 1998 in order to observe a few events per year [6]. The design concept of the LCGT was to increase the baseline of the TAMA by one order and to decrease the thermal fluctuations of the mirrors by one order by using cryogenics and by locating the LCGT at an underground site in Kamioka mine. The original plan has been revised to consider recent technical developments and the experience obtained in a data-taking-run by TAMA.

Cryogenic mirrors are adopted for the main cavities in the interferometer of the LCGT. Unfortunately, in place of the synthetic silica, sapphire crystal must be used for the material of the mirror substrate, which has a higher internal optical loss due to scattering and absorption [9]. This causes higher heat loss inside the near mirror of the Fabry-Perot cavity. In order to reduce the problem arising from the higher optical loss inside the near mirror, we apply the technique of the resonant sideband extraction (RSE) scheme [7] with low-power recycling gain. The other item that characterizes the LCGT is the suspension point interferometer (SPI), which is adopted in order to reduce the mechanical noise inevitably introduced by cooling devices through the mirror suspension system [5].

The data colleted by TAMA that was heavily contaminated by non-Gaussian noise produced many fake events. We intend to install two sets of interferometers separately housed in different vacuum systems into the same tunnel in Kamioka mine to enhance the rejection ratio of such fake events.

The cryogenic mirror allows us to design the sensitivity of the interferometer limited only by quantum noises: shot noise and pressure noise of photon recoil. If we can establish this quantum limited sensitivity, the sensitivity of the observational band is changed only by the signal bandwidth and the optical power in the cavity. By adjusting these two parameters, we can increase the detectable distance of the coalescence of the 1.4 $M_\odot$ neutron star binary with the signal-to-noise ratio, 10. Considering achievable technical condition, we fixed the optimum point at a power of 800 kW and a signal bandwidth of 200 Hz, which are realized by parameters listed in Table 1. From the detectable distance of 244 Mpc, we need to observe for 6 months to 5 years to obtain the first gravitational wave signal using the estimation of the distribution density of galaxies.

Table 1. Important parameters of the design of the LCGT

Item	Parameter
Baseline	3 km
Interferometer	Power recycled Fabry-Perot Michelson with RSE
Optical Power	Laser: 300 W, Cavity Finesse: 1250
	Power Recycling gain: 10, Effective power: 800 kW
Signal bandwidth	200 Hz, Signal recycling gain: 10
Mirror	Diameter: 30 cm, Thickness: 18 cm
	Mass: 51 kg, Material: Sapphire crystal
Acoustic loss angle	Mirror internal : 1×10^{-8}, Pendulum : 1×10^{-8}
	Optical coating: 4×10^{-4}
Temperature	Mirror: 20 K, Suspension: 10 K
Vacuum	$\leq 2 \times 10^{-7}$ Pa

In the optical design of the main interferometer of the LCGT, a 300-W Nd:YAG laser source is applied through two stages of mode cleaners to an RSE-type power-recycled Fabry-Perot-Michelson interferometer with a 3-km baseline length. Four main mirrors made of sapphire crystal are cooled to 20 K. Other optical pieces are maintained at room temperature. Figure 1 presents the noise limit attained by the design. The sensitivity in the main observation band is limited only by photon quantum noises: photon shot noise and photon pressure recoil noise.

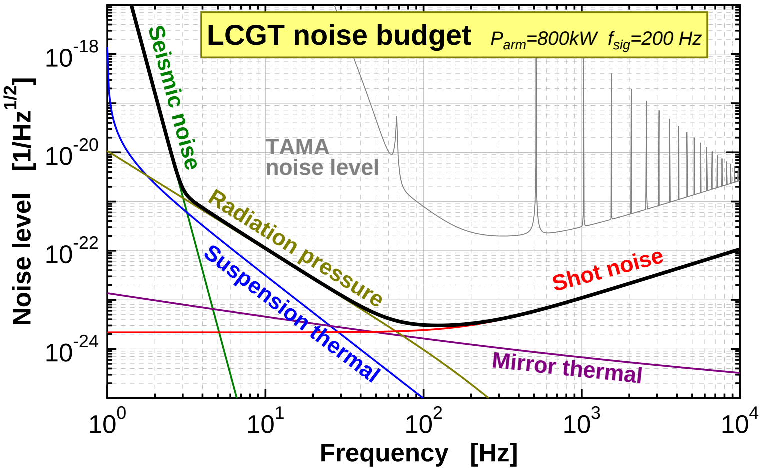

Fig. 1. Sensitivity limit attained by the LCGT.

The cryogenic mirror is made of sapphire and is suspended by sapphire fibers that extract heat produced at the mirror from optical loss inside the mirror to an intermediate mass that has adequate damping of the pendulum motion of the suspension system. The heat extraction from the intermediate mass is done using heat links of pure aluminum attached to a heat anchor located at the inner 4 K radiation shield of the cryostat. Since the heat conductivity of sapphire is optimum at around 20 K, the temperature of the mirror is designed as 20 K.

The interferometer system that is governed only by quantum noises requires a highly sophisticated isolation system in addition to a suspension system of similar quality. According to the original grand design of the suspension and anti-vibration system, we will install the suspension system into the cryostat and the seismic attenuation system (SAS) in a room temperature vacuum chamber mounted over the cryostat. The prototype system of SAS was originally developed at VIRGO [3] and later at CALTECH under collaboration with TAMA members [8]. The suspension platform suspending the mirror of an intermediate mass is supported by stainless steel wires from the final stage of SAS. The intermediate mass is a part of SPI that reduces the noise introduced through heat links to the cryogenic anchor point located at the 4 K radiation inner shield. The SPI mirror also suspends the main mirror by sapphire fibers. A prototype suspension system testing this original design is under development for a one-hundred-meter cryogenic interferometer (CLIO project) without an SPI system.

In conclusion, both successful results of TAMA and cryogenic R&D imply that the LCGT realizes the ultimate level of sensitivity attainable on the Earth. Practical R&D will be conducted during the course of the construction phase of the LCGT. We hope that the LCGT budget is approved in 2005.

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